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ECR-MAC: An Energy-efficient and Receiver-based MAC Protocol for Cognitive Sensor Networks in Smart Grid

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***Abstract*—Wireless Sensor Networks (WSNs) have been widely recognized as a promising solution for enhancing various aspects of electric power grid and realizing the vision of smart grid. However, energy crisis and challenging wireless environment in smart grid create a number of challenges for WSNs, as a result of which energy efficiency become critically important. On the other hand, cognitive radio (CR) technology is expected to play a vital role in smart grid networks. Cognitive Sensor Networks (CSNs) can effectively address some unique challenges of WSNs in smart grid. In this paper, we aim to design an energy efficient Medium Access Control (MAC) protocol for CSNs. In this regard, we propose ECR-MAC, which is an energy-efficient receiver-based MAC protocol for CSNs. ECR-MAC uses a energy-efficiency based auction mechanism and preamble sampling techniques for providing high energy efficiency and reliability. In addition, ECR-MAC explicitly accounts for the peculiarities of a CR environment. Analytical and simulation results demonstrate the effectiveness of ECR-MAC as a viable solution for CSNs.**

***Index Terms*—smart grid, wireless sensor networks, cognitive radio, MAC protocol, energy-efficiency**

I. Introduction

THE legacy electric power grid, which has been used for many years, meets some problems such as insecurity, energy inefficient and frequent transmission congestion and even failure [1]–[3]. The next generation of electric grid, namely, *smart grid*, is expected to supply improved serves with more reliability, efficiency, agility and security [4]–[6]. It will upgrade power distribution and management by incorporating advanced bi-directional communications, automated control and distributed computing capabilities. It makes providers distributors, and consumers of electricity can have a real time awareness of operating requirements and capabilities. The capacity gathers remote and timely information from grid equipment in different areas is critical for the successful operation of smart grid [7], [8].

Recently, wireless sensor networks (WSNs) [9] are gaining a lot of attention for electric power network [10], [11]. Reliable, efficient, and low cost operation and management of smart grid can be accomplished with the installation of wireless sensor nodes in different parts of grid such as distributed power plants, transmission towers and lines, substations, commercial/residential buildings, etc. Information gathered from these sensors can be used for many applications, such as distributed automation, smart metering, etc. Especially, application of wireless multimedia sensor networks enhances the reliability, safety, and security of smart grid [12]. However, the success of smart grid operation depends on the communication capabilities of sensor nodes in harsh environmental conditions that bring out great challenges for energy efficiency and reliability in WSNs.

On the other hand, several studies have been proposed for cognitive radio (CR) technology in smart grid communications (e.g., see [13]–[17]). More importantly, the use of $Cognitive\ Sensor\ Networks$ (CSNs)) has been proposed to address the challenges of WSNs in smart grid [18]. With dynamic spectrum access capabilities, CSNs can get high bandwidth and access of better propagation bands (e.g., TV white spaces [19]). Moreover, CSNs can adapt to varying channel conditions that improves the transmission efficiency, such that power consumption in transmission and reception modes can be minimized [20]. However, CSNs for smart grid is still an unexplored area [21]. Successful operation of CSNs in smart grid requires enhancements and optimizations at different layers of the protocol stack, especially at the Medium Access Control (MAC) layer. A receiver-based MAC protocol for CSNs is proposed in [21], which gets a trade-off between spectral efficiency and energy efficiency and provides reliable operation in smart grid wireless environments. However, the energy crisis threaten and rising energy price lead to a trend to improve the *energy efficiency* aspect of many applications.

Against this background, our objective in this paper is to improve the energy efficiency of MAC protocol for CSNs in smart grid. In this regard, we propose ECR-MAC (short for Energy-efficient Cognitive Receiver-Based MAC), which is a *receiver-based* MAC protocol for CSNs. ECR-MAC is designed with special emphasis on energy efficiency of CSNs operating in smart grid environments. In order to achieve high energy efficiency, ECR-MAC uses the transmission energy consumption as the key in next hop competition and employs *preamble sampling* [22] approach to tackle *idle listening* and support sleep/wakeup modes without synchronization overheads. ECR-MAC exploits the broadcast nature of wireless medium and adopts an auction mechanism approach with multiple receivers as discussed later in detail.

The rest of the paper is organized as follows. Section II describes the framework of ECR-MAC including the system model, protocol description and transmission energy computation. In Section III, numerical analytical and simulation performance evaluation are given. Finally, Section IV concludes the paper.

II. ECR-MAC Framework

A. ECR-MAC Overview

ECR-MAC is *receiver-based* in nature. Inherently, the receiver-based MAC is different from *sender-based* MAC. In sender-based MAC protocol, it is the sender that selects a receiver node from its neighbor table and includes the receiver's address in the packet header. However, in ECR-MAC, no particular nodes are defined as receivers. The sender node transmits the data packet by broadcasting such that all neighbor nodes in the communication range can receive the packets. Receivers compete in an *auction* process and the winner forwards the data to the next hop towards gateway.

In the auction process, the transmission energy consumption is the key factor. In ECR-MAC, the energy efficiency is attached much importance to. In the auction, each node that contends to forward data supplies an offer to show its energy consumption of single hop operation. When an offer is published, other nodes compare the energy consumption with its own. If the existing offer is better than its own, the node discards the competition. Otherwise, it supply its offer with a better energy consumption. The node giving the best offer will be the winner and forward the data. In this way, the receiver with highest energy efficiency wins and forward the data. The transmission energy consumption evaluation will be introduced in detailed later.

Another key aspect of ECR-MAC is using *preamble sampling* to improve the energy efficiency. In preamble sampling approach, each nodes uses asynchronous low power listening and select the sleep/wakeup schedules independently. The nodes spend most of their time in sleep mode and wake up for a short duration, namely, *clear channel assessment* (CCA) every *checking interval* (CI) to check whether there is an ongoing transmission. To avoid missed detection, the sender node transmits a long preamble longer than CI, before the data packet, to ensure that the preamble can be detected. By tuning CI and CCA, average duty-cycles of below 1% can be achieved without any need for scheduling or synchronization [21].

B. System Model

The ad-hoc network of stationary sensor nodes with CR ability is considered here. It is important to mention that the design of Physical (PHY) layer is beyond the scope of this paper. Challenges at the PHY layer of CSNs, such as low cost dynamic spectrum access solutions and low cost Software Defined Radio (SDR) based transceivers, are not studied in this paper.

We consider J stationary PU transmitters (and hence J available channels) with known locations and maximum coverage ranges. The PU (transmitter) activity model for the j^{th} channel is given by a two state independent and identically distributed random process, namely, $busy$ and $idle$. Let S_b^j denote the state that the j^{th} channel is busy (PU is active) and S_i^j the state that the j^{th} channel is idle with probability. We assume that a node employs energy detection technique [23] for primary signal detection wherein it compares the received energy (E) with a predefined threshold (σ) to decide whether the j^{th} channel is occupied or not i.e.,

$$Sensing\ Decision = \begin{cases} S_b^j & \text{if} \quad E \geq \sigma \\ S_i^j & \text{if} \quad E < \sigma \end{cases} \tag{1}$$

The two principle metrics in spectrum sensing are the detection probability (P_d), and the false alarm probability (P_f). A higher detection probability ensures better protection to incumbents, whereas a lower false alarm probability ensures efficient utilization of the channel. False alarm and detection probabilities for the j^{th} channel can be expressed as follows.

$$P_f^j = Pr\{E \geq \sigma | S_i^j\} = Q\left(\frac{\sigma - 2n_j}{\sqrt{4n_j}}\right), \tag{2}$$

$$P_d^j = Pr\{E \geq \sigma | S_i^j\} = Q\left(\frac{\sigma - 2n_j\left(\gamma_j + 1\right)}{\sqrt{4n_j\left(2\gamma_j + 1\right)}}\right), \tag{3}$$

where $Q(\cdot)$ accounts for Q function, which is the complementary error function, and γ_j and n_j denote the signal-to-noise ratio (SNR) of the primary signal and the bandwidth-time product for the j^{th} channel respectively.

The MAC frame structure in a CR network consists of a sensing slot (T_s) and a transmission slot (T). In periodic spectrum sensing scenarios, there is a possibility of causing harmful interference to PUs due to imperfect spectrum sensing in realistic conditions. This interference is quantified in terms of *Interference Ratio* (IR), defined as the expected fraction of ON duration of PU transmission interrupted by the transmission of secondary users and is given for the j^{th} channel as follows [21].

$$IR_j = \left(1 - P_d^j\right) P_b^j + P_i^j \left(1 - P_f^j\right) + e^{-\mu T}\left(P_f^j - P_d^j\right), \tag{4}$$

where $\mu = \max(\mu^j_{ON}, \mu^j_{OFF})$. We assume that the nodes in our network employ optimal transmission time that maximizes the throughput of the secondary network subject to an interference constraint i.e., $IR_j \leq IR^j_{max}$, where IR^j_{max} denotes the maximum tolerable interference ratio on the j^{th} channel.

C. Protocol Description

In ECR-MAC, different from the *sender-based* mechanism (such as 1-hopMAC in literature [24]), nodes need not select a particular receiver. The sender broadcast the data packet. It is the receiver nodes that decide the next hop node. The sender node S is to send data to the gateway by broadcasting the packet towards all its hop neighbors (within the transmission range). Firstly, it performs spectrum sensing (with duration given by T_s) to detect any PU activity. If the channel is detected as busy with PU transmission, namely, S^j_b, the S goes to sleep mode and waits for the available channel. The spectrum sensing operation is repeated after a duration of checking interval (T_{CI}). If the PU is detected to be absent, namely, S^j_i, S starts broadcasting the preamble. The preamble, which last for T_{pr}, consists of multiple micro-frames. Each micro-frame lasts T_m. The micro-frames contain identification information for neighboring nodes to distinguish between PU transmission or sensor node transmission. All the nodes within the transmission range of S will detect a few micro-frames of the preamble and extract necessary information (e.g., sequence number of the data).

We note that in next hop competition, the transmission energy consumption is the determining factor. The receiver with best transmission energy consumption will be the winner and forward the packet. For example, three neighboring nodes of S (i.e., nodes A, B, and C) are eligible to forward the data towards the gateway node. They wake up and receive the data transmitted from S, when they find the preamble. If the received data packet is detected to be erroneous, it will be simply discarded. The nodes, which received the data packet do not send any Acknowledgement (ACK) message. If a node (e.g., A) wants to forward the packet, it waits for a timer Δt_A and begins sensing the spectrum. When a channel is available, A broadcasts a preamble to give a offer of transmission energy consumption (the compute of transmission energy consumption will be introduced detailedly later). After that, it waits for other better offer for a duration T_{CI} before forwarding the data to the next hop. If another node supplies a better offer in T_{CI}, A will discard the transmission; else A will begin the data broadcast. If A does not begin the transmission in t_m, its offer will be cancelled and other nodes can contend with its own offer. Node B receives A's offer and finds that its own transmission energy consumption better than A's. Therefore, B broadcasts its offer when a channel is available. Similarly, B also waits for better offer from other nodes in T_{CI} before data transmission.

In addition, the sender node S retransmits the data if none of the participating nodes in the contention window transmits the preamble to supply the offer. The sender node can realize this by performing the sensing operation just before ending the contention window (T_{CW}). The duration of contention window is set according to the transmission radius of sender nodes. In case of multiple hops, the same operation continues until the data is received by the gateway.

Moreover, a technique is adopted in ECR-RPL for mitigating the performance degradation due to spectrum sensing. Its key character is to improve the performance by reducing the spectrum sensing time. Reduction of sensing time is possible when a node is situated in region of low PU activity, as nodes need change channels randomly. Initially, the sensing time is set to the maximum value i.e., $T_s = T^{max}_s$ for a fixed missed detection probability ($P^j_m = 1 - P^j_d$). When the node get a available channel successfully, it will decrease the sensing time according to the following relation: $T^{new}_s = T_s - \varphi \cdot \Delta_s$, where Δ_s is the step size, which is set as $\Delta_s = 0.25 \times T_s$ in this paper, and φ is a constant which is obtained from the gradient of sensing time versus the missed detection probability curve (see [25] for more details). When successive missed detection events occur, the node increases the sensing time with similar step size.

D. Transmission energy consumption evaluation

Under realistic conditions, there exists inaccuracy in spectrum sensing, which may lead to transmission failure of both PU and secondary network users. Let P^j_{sw} denote the probability of switching transmission to the j^{th} cognitive channel for a node (e.g., node i). P^j_{sw} can be evaluated considering two cases, namely, S^j_i and S^j_b without being detected. Therefore, P^j_{sw} is given by

$$P^j_{sw} = P^j_b \left(1 - P^j_d\right) + P^j_i \left(1 - P^j_f\right) \tag{5}$$

Therefore, the failure probability of transmission on the j^{th} channel depends on the corruption in preamble or data frame, which is given by

$$P^j_{fail} = P^j_{sw} \left[1 - (1-p)^{m+d}\right], \tag{6}$$

where m, d and p denote the size of micro-frame and data frame in bits and the bit error probability, respectively.

Let, r_m denote the number of micro-frames in the preamble and T_m is the transmission time for one micro-frame. When receiving packets, the nodes detect the preamble transmission during spectrum sensing if the PU is not active first. The expressions for energy drained in a single successful and failed transmission on the j^{th} channel are given by

$$\mathcal{E}\_R^j_{succ} = \mathcal{E}^j_{ss} + P^j_{sw} \left\{(1-p)^m(\tau + T_s) + (1-p)^d(\tau + T_d\right\} \mathcal{P}_r, \tag{7}$$

$$\mathcal{E}\_R^j_{fail} = \mathcal{E}^j_{ss} + P^j_{sw} \left\{(\tau + T_s) + \left(1 - (1-p)^d\right)(\tau + T_d)\right\} \mathcal{P}_r, \tag{8}$$

where $\mathcal{P}_r$ denotes the power drained in the receive mode.

In case of a failed transmission, the sender node will retransmit the data. The number of retransmission until successful transmission is computed based on $Expected\ Transmission\ Count$ (ETX), which is given by $ETX = 1/\rho$, where ρ is the probability of a transmission between two nodes. Therefore, the energy consumption for a node to receive a packet successfully is given by

$$\mathcal{E}_R^j = (\rho_{sr} - 1)\mathcal{E}\_R_{N\_fail}^j + \mathcal{E}\_R_{succ}^j + \chi_{ss}^j \mathcal{E}_{ss}^j \quad (9)$$

where $\mathcal{P}_t$ denotes the power drained in the transmit mode, T_d denotes the duration of data frame, $\mathcal{E}_{pp}$ denotes the energy drained in the preamble processing, $\mathcal{E}_{ss}^j$ denotes the energy drained during spectrum sensing, and χ_{ss}^j denotes the expected number of sensing events for transmitting over the j^{th} channel, respectively.

The energy drained during spectrum sensing, i.e., $\mathcal{E}_{ss}^j$, is given by

$$\mathcal{E}_{ss}^j = (\tau + T_s)\mathcal{P}_s, \quad (10)$$

where $\mathcal{P}_s$ and τ denote the power required for spectrum sensing operation and the transition time from sleep mode to active mode, respectively.

The expected number of sensing events for transmitting over the j^{th} channel, i.e., χ_{ss}^j, is given by

$$\chi_{ss}^j = \sum_{l=0}^{\infty} l \cdot (1 - P_{sw}^j)^l P_{sw}^j = \frac{1 - P_{sw}^j}{P_{sw}^j} \quad (11)$$

where $\mathcal{P}_s$ and τ denote the power required for spectrum sensing operation and the transition time from sleep mode to active mode, respectively.

On the transmitter side, the energy consumption of node broadcast the packet can be evaluated based on Shannon's theorem. We assume the minimum of requested rate demand is R_d. Thus, the channel capacity should satisfy the following condition

$$C_i = W_i \log_2 (1 + SNR_i) \geq R_d \quad (12)$$

Thus, the minimum required power for transmission over the ith channel is given by

$$\mathcal{P}_i^{min} = \frac{\left(2^{\frac{R_d}{\mathbb{P}_{acc}^k}} - 1\right)\delta^2}{|h_i^2|} \quad (13)$$

where h_i is the channel coefficient, given by

$$h_i = F_i \sqrt{1/L_i} \quad (14)$$

where F_i is the fading coefficient of the channel while L_i is the path loss and computed based on Okumura model [26].

Therefore, the energy consumption for transmission is given by

$$\mathcal{E}_T^i = \mathcal{P}_i^{min} \cdot T_p \quad (15)$$

where T_p accounts for the duration of transmitting the packet, which is related to the packet.

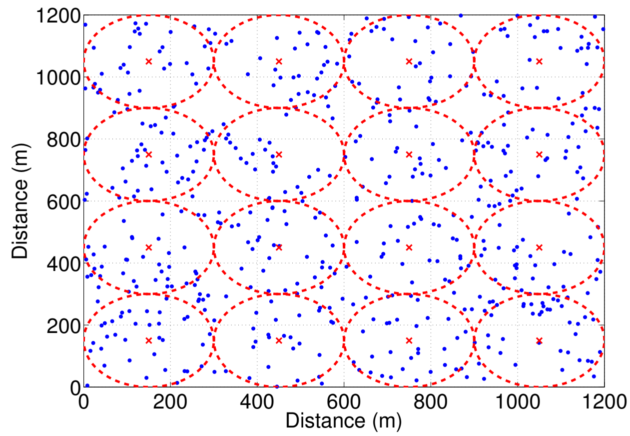

Fig. 1. Sample simulated topology with Poisson distributed nodes (density = 300 nodes per square kilometers). The filled squares and dotted circles represent the location and coverage area of PU transmitters respectively.

The total energy consumption for a node over a single hop insists of three parts, namely, receiving energy consumption, preamble process energy consumption and transmission energy consumption, which is given by

$$\mathcal{E}_{total} = \mathcal{E}_R^j + \mathcal{E}_{pp} + \mathcal{E}_T^i \quad (16)$$

III. Performance Evaluation

In this section, we evaluate the single hop and multi-hop performance of ECR-MAC. We perform a MATLAB based simulation (with parameters given in TABLE I) to validate the analytical models. A square region of side 1200 meters is considered that is occupied by 16 PU transmitters. The secondary users are assumed to be Poisson distributed in the whole region with a mean density as shown in Fig. 1. Without loss of generality, we assume that RPL is operating at the Network layer. The transmission radius of each node is set to 40 meters. Moreover, we assume that each node is equipped with *Texas Instruments* CC2500 Radio Transceiver whose parameters are also given in TABLE I.

We implement a sender-based MAC protocol (1-hopMAC [24]) in CR environments (CSB-MAC) and a receiver-based MAC protocol (CRB-MAC) for comparison.

In Fig. 2, we evaluate the energy consumption performance of ECR-MAC (based on analytical models) against bit error rate (BER). In channels with rather low BER, ECR-MAC and CRB-MAC outperform the CSB-MAC in terms of energy consumption. This is because ECR-MAC and CRB-MAC have less retransmissions than CSB-MAC owing to multiple receivers involved in the forwarding process, which is determined by the nature difference between receiver-based mechanism and sender-based mechanism. Between ECR-MAC and CRB-MAC, the former has a better performance, since energy-efficiency is emphasized in ECR-MAC. The energy consumption is increasing with the BER for all the three MAC protocols. This because higher BER leads to

TABLE I
SIMULATION CONFIGURATION PARAMETERS

Parameter	Value
Detection probability threshold (P_d')	0.9
Probability of false alarm (P_f)	0.1
Channel bandwidth	200 KHz
PU received SNR (γ)	-15 dB
Busy state parameter of PU (μ_{ON})	2
Idle state parameter of PU (μ_{OFF})	3
Maximum Interference Ratio (IR_{max})	0.25
Spectrum sensing duration (T_s)	20 ms
CC2500 RF Transceiver Parameters	
Power drained in transmit mode ($\mathcal{P}_t$)	66.16 mW
Power drained in receive mode ($\mathcal{P}_r$)	70.69 mW
Power drained in spectrum sensing ($\mathcal{P}_s$)	65.83 mW
Checking interval (T_{CI})	144 ms
Preamble length (T_{pr})	144 ms
Transmission time of a data packet (T_d)	4 ms
Transmission time of one micro-frame (T_m)	40 μs
Transition time from sleep mode to active mode (τ)	88.4 μs

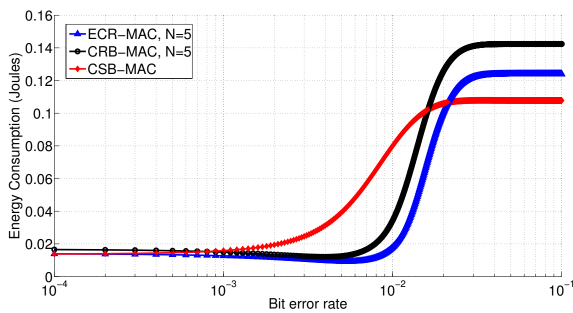

Fig. 2. End to end energy consumption against bit error rate, N represents the number of receivers

higher probability of retransmission. In very poor channel conditions, CRB-MAC and ECR-MAC consumes more energy than CSB-MAC. The energy consumption reaches a saturation point when the maximum number of retransmissions is reached. Therefore, the high energy consumption of receiver-based protocols in poor channel conditions is primarily due to more receivers involved in the forwarding process. However, ECR-MAC has a better performance than CRB-MAC, since the preamble and data are transmitted respectively in forwarding in ECR-MAC and nodes discard to receive data if error bits are found in the preamble. it is also noted that CSB-MAC reaches the saturation point quickly as soon as the BER starts to degrade. However, ECR-MAC shows more resiliency and stays operational, even when CSB-MAC has failed.

Next, we evaluate the energy consumption performance against the number of hops of ECR-MAC in both good (low BER with $p = 0.025$) and poor channel (high BER with $p = 0.25$) conditions. In Fig. 3, the simulation results are given. In simulations, we generate $10,000$ packets from different nodes and average the results for different performance metrics. We note that the energy consumption increases with

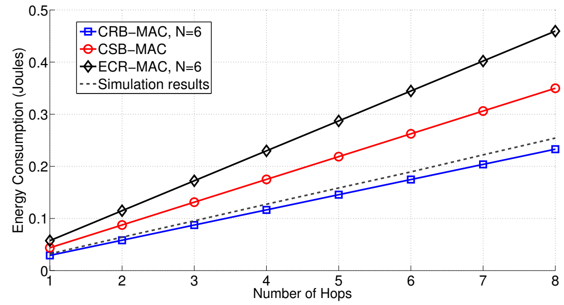

Fig. 3. Multi-hop performance of energy consumption

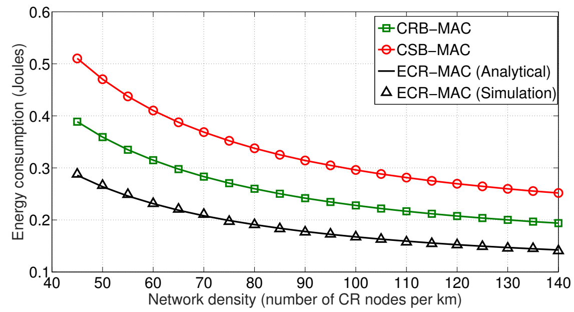

Fig. 4. Energy consumption performance of ECR-MAC against node density

the number of hops, with ECR-MAC outperforming CSB-MAC and CRB-MAC in low BER conditions. In high BER conditions, the energy consumption of ECR-MAC increases due to higher energy consumption in the reception process as mentioned earlier. We note that the simulation results follow the analytical results, which can validate the analytical modeling. Slight difference between simulation results and analytical results is due to the fact that nodes are randomly distributed in simulations and therefore, the number of receivers at each hop varies. Some nodes may have fewer neighbors than others within the transmission range.

Then, we evaluate the average single hop energy consumption performance against the node density. In Fig. 4, energy consumption decreases as node density increases. This is because in higher node density environment, more receivers are in the transmission range of a sender, which increase the probability of receiver with better energy efficiency. We note that ECR-MAC has low energy consumption than other two protocols. This because in ECR-MAC, it is the receiver with best energy-efficiency that wins the receiver competition. Moreover, we can see that the simulation results follow the analytical results.

Last, we discuss the reliability performance in Fig. 5. We note that ECR-MAC provides a good *Packet Delivery Rate* (PDR) performance (obtained through simulations) under both good and poor channel conditions. ECR-MAC and CRB-MAC have better performance than CSB-MAC due to the receiver-based nature. Inherently, ECR-MAC and CRB-MAC

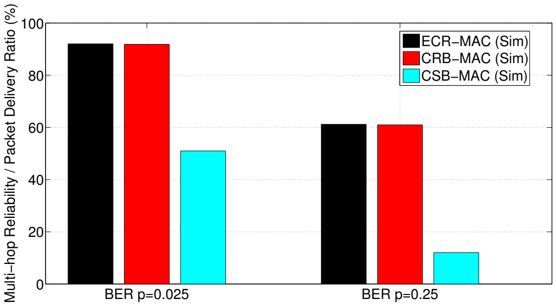

Fig. 5. Multi-hop reliability performance of ECR-MAC in low BER and high BER environments

are both receiver-based and therefore, these two have close performance. We also note that in good network condition (BER=0.025), the PDR of ECR-MAC can achieve about 2 times of CSB-MAC. In the channel with high BER, PDR of ECR-MAC can still achieve 60%, while PDR of CSB-MAC is about 15%. Therefore, we can know that ECR-MAC has a good reliability.

IV. Concluding Remarks

In this paper, we have proposed ECR-MAC, which is a receiver-based MAC protocol for CSNs. ECR-MAC employs an energy-efficiency based auction mechanism in the next hop competition such that the receiver with the best transmission energy-efficiency as the forwarder node. Furthermore, the preamble sampling is adopted to cater for high energy efficiency and reliability requirements of CSNs. Analytical and simulation results demonstrate that in lossy wireless environments ECR-MAC generates less retransmissions and therefore, enhances the overall energy performance. Moreover, high reliability can be provided by increasing the number of receivers due to the receiver-based nature. Hence, ECR-MAC provides a viable solution for CSNs in realizing the vision of smart grid.

References

[1] C.-H. Lo and N. Ansari, "The progressive smart grid system from both power and communications aspects," *Communications Surveys & Tutorials, IEEE*, vol. 14, no. 3, pp. 799–821, 2012.

[2] H. Sun, A. Nallanathan, B. Tan, J. S. Thompson, J. Jiang, and H. V. Poor, "Relaying technologies for smart grid communications," *Wireless Communications, IEEE*, vol. 19, no. 6, pp. 52–59, 2012.

[3] E. Hossain, Z. Han, and H. V. Poor, *Smart grid communications and networking*. Cambridge University Press, 2012.

[4] S. M. Amin and B. F. Wollenberg, "Toward a smart grid: power delivery for the 21st century," *Power and Energy Magazine, IEEE*, vol. 3, no. 5, pp. 34–41, 2005.

[5] L. Sankar, S. Kar, R. Tandon, and H. V. Poor, "Competitive privacy in the smart grid: An information-theoretic approach," in *Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on*. IEEE, 2011, pp. 220–225.

[6] W.-Y. Chiu, H. Sun, and H. V. Poor, "Demand-side energy storage system management in smart grid," in *Smart Grid Communications (SmartGridComm), 2012 IEEE Third International Conference on*. IEEE, 2012, pp. 73–78.

[7] K. C. Budka, J. G. Deshpande, T. L. Doumi, M. Madden, and T. Mew, "Communication network architecture and design principles for smart grids," *Bell Labs Technical Journal*, vol. 15, no. 2, pp. 205–227, 2010.

[8] H. Sun, A. Nallanathan, N. Zhao, and C.-X. Wang, "Green data transmission in power line communications," in *Global Communications Conference (GLOBECOM), 2012 IEEE*. IEEE, 2012, pp. 3702–3706.

[9] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," *J. Comput. Networks*, vol. 38, no. 4, pp. 393 – 422, 2002.

[10] V. Gungor, B. Lu, and G. Hancke, "Opportunities and Challenges of Wireless Sensor Networks in Smart Grid," *IEEE Trans. Indust. Electronics*, vol. 57, no. 10, pp. 3557–3564, Oct 2010.

[11] Y. Yang, F. Lambert, and D. Divan, "A Survey on Technologies for Implementing Sensor Networks for Power Delivery Systems," in *IEEE Power Engineering Society General Meeting*, June 2007, pp. 1–8.

[12] M. Erol-Kantarci and H. T. Mouftah, "Wireless Multimedia Sensor and Actor Networks for the Next Generation Power Grid," *J. Ad-Hoc Networks*, vol. 9, no. 4, pp. 542 – 551, 2011.

[13] R. Qiu, Z. Hu, Z. Chen, N. Guo, R. Ranganathan, S. Hou, and G. Zheng, "Cognitive Radio Network for the Smart Grid: Experimental System Architecture, Control Algorithms, Security, and Microgrid Testbed," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 724–740, 2011.

[14] A. Ghassemi, S. Bavarian, and L. Lampe, "Cognitive Radio for Smart Grid Communications," in *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2010, pp. 297–302.

[15] R. Deng, J. Chen, X. Cao, Y. Zhang, S. Maharjan, and S. Gjessing, "Sensing-Performance Tradeoff in Cognitive Radio Enabled Smart Grid," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 302–310, 2013.

[16] M. Brew, F. Darbari, L. Crockett, M. B. Waddell, M. Fitch, S. Weiss, and R. Stewart, "UHF White Space Network for Rural Smart Grid Communications," in *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2011, pp. 138–142.

[17] J. Huang, H. Wang, Y. Qian, and C. Wang, "Priority-Based Traffic Scheduling and Utility Optimization for Cognitive Radio Communication Infrastructure-Based Smart Grid," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 78–86, 2013.

[18] A. Bicen, O. Akan, and V. Gungor, "Spectrum-Aware and Cognitive Sensor Networks for Smart Grid Applications," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 158–165, 2012.

[19] M. Nekovee, "Quantifying the Availability of TV White Spaces for Cognitive Radio Operation in the UK," in *IEEE International Conference on Communications (ICC) Workshops*, 2009, pp. 1–5.

[20] O. Akan, O. Karli, and O. Ergul, "Cognitive Radio Sensor Networks," *IEEE Network*, vol. 23, no. 4, pp. 34–40, July 2009.

[21] A. Aijaz, S. Ping, M. R. Akhavan, and A.-H. Aghvami, "Crb-mac: A receiver-based mac protocol for cognitive radio equipped smart grid sensor networks," *Sensors Journal, IEEE*, vol. 14, no. 12, pp. 4325–4333, 2014.

[22] A. El-Hoiydi, "Aloha with Preamble Sampling for Sporadic Traffic in Ad-hoc Wireless Sensor Networks," in *IEEE International Conference on Communications (ICC)*, vol. 5, 2002, pp. 3418–3423 vol.5.

[23] H. Sun, W.-Y. Chiu, J. Jiang, A. Nallanathan, and H. V. Poor, "Wideband spectrum sensing with sub-nyquist sampling in cognitive radios," *arXiv preprint arXiv:1302.1847*, 2013.

[24] T. Watteyne, A. Bachir, M. Dohler, D. Barthel, and I. Auge-Blum, "1-hopMAC: An Energy-Efficient MAC Protocol for Avoiding 1-hop Neighborhood Knowledge," in *IEEE International Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, Sept 2006, pp. 639–644.

[25] K. R. Chowdhury, M. D. Felice, and I. F. Akyildiz, "Tp-crahn: A transport protocol for cognitive radio ad-hoc networks," in *INFOCOM 2009, IEEE*. IEEE, 2009, pp. 2482–2490.

[26] J. S. Seybold, *Introduction to RF propagation*. John Wiley & Sons, 2005.